SECTION IV
CONCLUSIONS

Throughout the period of this study, the Fuel Cell Technical Advisory Panel reviewed, updated and discussed the information obtained from its sources, as summarized in the preceding sections of this report. The Panel members have agreed on the following conclusions and supporting information regarding the current development status of PEM fuel cells and their prospects for becoming a widely adopted, fundamentally cleaner and more efficient automotive engine.

1. Hydrogen-air PEM fuel cell stack technology has advanced to the point where performance and operating characteristics meet the requirements for automobile propulsion.

Major technology advances over the past 5-7 years in every aspect of cell and stack technology have raised the performance of PEM hydrogen-air fuel cell stacks to more than 1 kW/liter, sufficient for automotive applications. In particular, membrane-electrode assemblies made from Nafion-type proton exchange membranes and advanced catalysts have demonstrated excellent performance and durability; they are now available in pilot quantities from several suppliers. Leading fuel cell developers have started to engineer stacks for low-cost volume production and are developing the required mass-manufacturing processes. Ballard Power Systems expects to freeze the design for its production stack in 1999; pilot manufacturing is scheduled to begin in 2000, full-scale production (production rate of about 40,000 stacks per year) in 2004.

2. Hydrogen is not a feasible fuel for private automobiles now nor in the foreseeable future because of the difficulties and costs of storing hydrogen on board and the very large investments that would required to make hydrogen generally available

Storing adequate amounts of hydrogen onboard automobiles as compressed gas is technically very difficult because of the large volume required. Storing hydrogen as a liquid is inefficient and expensive, and metallic hydrogen storage alloys are heavy as well as expensive. The establishment of production and distribution infrastructures to make hydrogen generally available would cost several hundred billion dollars and add at least $2-4 to the cost of hydrogen per gallon of gasoline energy equivalent. Smaller hydrogen supply infrastructures would have similar cost impacts and leave open the question whether local and/or regional deployment of hydrogen-fueled automobiles could result in the annual production rates (100,000 vehicles or more) needed to achieve the economics of mass production.

3. **The issues surrounding hydrogen, and the strong preference of car makers for readily stored, affordable liquid fuels, have led automotive developers (including several that started with hydrogen) to focus their strategies on methanol and/or gasoline, despite the greater fuel cell engine complexities and costs. Methanol has been selected as the preferred fuel by the majority of developers but gasoline is being considered increasingly in the United States. The technical, economic and policy bases for a rational selection between methanol and gasoline are not likely to be available until fuel processor technology development efforts have proceeded further and the infrastructure and environmental implications of different fuel choices are better understood.**

Due to their insufficient electrochemical reactivity, methanol and gasoline (and other carbonaceous fuels) cannot be used directly in PEM fuel cell electric engines but must first be chemically processed into hydrogen-rich gases. Large-scale chemical processes for conversion of carbonaceous fuels into hydrogen-rich fuel gases are well established, but the development of fuel processors with the high power density (compactness), rapid start-up and dynamic response, high efficiency, near-zero emissions and very low cost needed for automobile applications represent new, very difficult development challenges. Important advances have been made and substantial creativity has been demonstrated by several developers, but developmental methanol and gasoline fuel processors do not yet meet startup and compactness requirements.

Methanol has been selected by European, Japanese and several U.S. automotive fuel cell developers because it is considered easier to process than gasoline and expected to permit achievement of somewhat higher fuel efficiency and lower overall carbon dioxide emissions. Longer term arguments for methanol include reduced strategic dependence on oil imports, and the possibility that technical breakthroughs could make the direct methanol fuel cell, now in the research stage, a candidate for automobile applications.

The future availability of adequate methanol production and distribution capacities has been raised as a potential issue. The methanol industry claims that modern plants for production of cost-competitive methanol from natural gas could be put on line at the rate and costs required by an expanding population of fuel cell electric vehicles. The establishment of methanol supply infrastructures is the subject of ongoing discussions between automobile manufacturers and the methanol and oil industries.

The development of gasoline processors for automobile applications started more recently, primarily in U.S. programs. The basic feasibility of processing gasoline into a reformate suitable for PEM fuel cell stacks has been established on the breadboard level but it is not yet clear whether and to what extent ordinary pump gasoline could be used over longer periods in automotive fuel processors. The best petroleum-derived fuel for fuel cell engines may be a broad distillate cut from which sulfur has been very largely removed at the refinery and which does not contain any of the gasoline additives that are necessary for good performance of combustion engines but may be detrimental to fuel cells.

3. The integration of stacks, fuel processors and balance-of-plant components into complete fuel cell electric engines poses a number of very difficult technical challenges. Nevertheless, systems integration has reached the breadboard stage in the leading programs, and Daimler-Benz has achieved the first in-vehicle operation of an experimental methanol-air fuel cell engine. While not yet a prototype, D-B's NeCar 3 vehicle demonstrates the basic feasibility of powering an automobile with a methanol fuel cell, and the first tests (which excluded cold start) support the expectation of extremely low emissions.

Increasing efforts are now underway to integrate PEM fuel cell components and subsystems into fuel cell engines and, in turn, integrating these engines physically and functionally into fuel cell electric vehicles. Breadboard-level integration of key subsystems has been demonstrated in Europe (Daimler-Benz), the United States (General Motors) and Japan (Toyota), and it is being pursued in several programs funded cooperatively by the Department of Energy and several U.S. industrial teams that include Ford and Chrysler. However, even the most advanced systems do not represent prototypical technology with respect to packaging, manufacturability of components, or key characteristics such as cold start time.

Daimler-Benz is the first automobile manufacturer to integrate all necessary fuel cell engine components and subsystems into the NeCar 3 vehicle which uses the Mercedes A-Class platform. In September 1997, NeCar 3 demonstrated the on-road operability of a 50 kW methanol PEM fuel cell electric engine, but this vehicle is not yet a prototype. The first dynamometer measurements indicated zero NO_x and CO and extremely low total hydrocarbon emissions for a modified FTP test mode (excluding cold start) but the data were not yet validated statistically at this writing. General Motors has constructed an integrated 30 kW methanol fuel cell system in their laboratory to demonstrate feasibility and study integration issues. In October 1997, Toyota presented the concept of the company's fuel cell electric vehicle ("FCEV") which features a PEM methanol fuel cell-battery hybrid engine and uses the RAV 4 platform. The concept car suggests a high degree of physical integration but no information on its practical realization and characteristics has been made available by Toyota.

4. The largest challenge in automotive fuel cell development is the achievement of electric engine costs that can compete with the very low per-kW costs of mass-manufactured internal combustion engines. This requirement translates into stringent cost goals for every material, component, manufacturing step and assembly operation. Such low costs are unprecedented in the fuel cell field and achievable only with mass-manufacturing methods. Most of the methods required have not yet been developed in current programs but no fundamental barriers to their development were identified.

Less than five years ago, the prospects for fuel cells as automobile engines seemed rather remote. Since then, impressive advances have raised the prospects that PEM fuel cell technology might be able to meet the performance requirements for automotive applications, bringing into sharp focus the extremely low cost goal for fuel cell automobile engines. At perhaps $3000 for a complete 50-60 kW engine, the per-kW goal is $50 to 60, less than 10% of the most ambitious — and as yet unattained — target of about $1,000/kW for stationary fuel cell power generators.

Breaking down the $3000 goal into approximate targets for the cost-critical subsystems and components, the Panel concluded from the preliminary and generally incomplete cost projections it obtained that the stack cost target of approximately $1000 ($20/kW) may be achievable in large volume production (>100,000 stacks per year). The few available fuel processor cost projections suggest that the $1000/kWe goal may be attainable. However, these projections need to be viewed with caution because they are not yet based on technology that meets all technical requirements and is engineered for mass production. Large reductions from the present cost of major balance-of-plant components — including air handling turbomachinery, controls, and the power conditioner — will be necessary to meet the targets for automobile applications.

Use of automated mass manufacturing methods for every component, subsystem and the entire fuel cell engine will be essential if the stringent cost targets are to be met. The leading PEM fuel cell system developers and key component suppliers have begun to develop these methods; to date, no fundamental barriers seem to have been encountered.

5. The performance, systems integration and manufactured cost goals for competitive PEM fuel cell electric engines are now being pursued by a remarkable number and combination of world-class organizations that have the diverse capabilities and are investing the large resources required to achieve these goals. The first go/no-go decisions on the billion dollar-level investments required for fuel cell engine mass manufacturing facilities are likely to occur by the year 2000. In a complete success scenario, fuel cell electric engines and vehicles could become commercially available from 2-3 automobile manufacturers beginning in 2004/2005.

Perhaps the most encouraging observations for the prospects of automotive fuel cells are the major commitments already made — and additional commitments being made and expected — by the types of organizations whose participation and leadership is essential if a commercially viable fuel cell electric engine and industry are to emerge: major automobile manufacturers in the United States, Europe and Japan with track records in advanced automotive technology; the world's leaders in PEM fuel cell technology; and world-class industrial organizations with leading technical positions and growing business interests in critical PEM fuel cell components. Powerful development and commercialization alliances and committed business arrangements have been formed between a number of these organizations, and government R&D programs are providing important support. In the Panel's estimate, the R&D investments already made and the commitments for the next two years already total between $1.5 and 2 billion.

The largest and most advanced integrated development effort — the alliance of Ballard Power Systems, Daimler-Benz and Ford — is aiming for a go/no-go decision on the investment in fuel cell engine manufacturing facilities by the end of 1999. A go-ahead decision will result in investments of ≥$1 billion and the adoption of a schedule for production of thousands of engines by 2002, 40,000 per year by 2004 and about 100,000 per year by 2006. Daimler-Benz has set 2004 as the year for commercial introduction of several 1000 fuel cell electric vehicles, and top executives of General Motors and Toyota have publicly stated similar intents of their organizations. Given the current status of the leading programs, the steps still ahead, and the limited time available for their completion, success at every turn and manufacturing investment decisions at the earliest possible time will be required to commercialize fuel cell electric engines and vehicles in a short 6 years from now.

6. The prospects for successful development and commercialization of fuel cell electric engines and vehicles in the coming decade still have substantial uncertainties and risks associated with them. The main technical uncertainties are likely to become

resolved and the largest cost uncertainties substantially reduced during the next 2-3 years. During the same time, fuel choice(s) and specifications should become clear. The ultimate uncertainty — acceptance of fuel cell electric vehicles by customers — can be reduced only gradually as user experience with prototypical and market test vehicles is being acquired in the subsequent 2-3 years, in parallel with further engineering and manufacturing development, testing, demonstration and manufacturing of automotive fuel cell electric engines and vehicles. During the entire period, organizations investing in automotive fuel cell development and commercialization will be facing substantial financial and business risks, with automobile manufacturers taking largest financial risks for the longest period — until substantial customer acceptance is established.

The largest technical uncertainties in the development of PEM fuel cell electric engines arise from the as yet incomplete development of fuel processors and their integration with PEM stacks and key balance-of-plant components into complete fuel cell engines. Other significant uncertainties with important technical and cost implications include the level of stack pressurization and the decision for or against hybridization of the electric vehicle drive. These uncertainties should be much reduced during the next few years as ongoing efforts result in a better understanding and optimization of the trade-offs between desirable performance and operating characteristics (such as rapid cold start) on the one hand and the associated complexity and costs on the other.

The cost projections for the major fuel cell engine subsystems and the lowest levels achievable in mass production are still quite uncertain, especially for fuel processors and balance-of-plant components. The leading programs aim for a positive resolution through engineering-for-low-cost and manufacturing development within 2-3 years from now. Additional conceptual advances and technology development may still be required to achieve cost targets for critical components and/or subsystems.

The choice of fuel(s) for automotive fuel cells is another major uncertainty. The growing involvement of the methanol and oil industries in collaborations with automobile manufacturers engaged in fuel cell engine and vehicle development is expected to result in the identification of technically and economically preferred fuel choice(s) and the formulation of collaborative fuel strategies in the next several years. Implementation of one or more of these strategies (which may differ in different countries or regions) could be the next step.

A remarkable number of automobile manufacturers, PEM fuel cell technology developers and developers/suppliers of critical components appear ready to assume the risks stemming from the current uncertainties. Their motivation is the progress already achieved and the prospect of potentially very large markets for a fundamentally cleaner and more efficient automobile engine; indeed, one can observe a sense of international and national competition emerging in this area. There is little doubt, however, that the regulatory initiatives of the California Air Resources Board were and are important factors in stimulating interest and investment in fuel cells as clean power sources for automobiles.

Strategies to Reduce Risks and Foster Needed Investments

While the Panel was not asked to develop formal recommendations on the basis of its findings and conclusions, it offers the suggestions below on some strategies that regulatory and other agencies might follow in trying to foster development and introduction of automotive fuel cells. The Panel recognizes that some or all of these strategies are already being discussed and considered. They are presented here to reflect the interests and concerns of the Panel's information sources — in particular major automobile manufacturers in the United States, Europe and Japan — in these possibilities and issues.

1. Develop and promulgate supportive regulatory positions on fuel cell electric vehicles.

There was general agreement that an early, clear regulatory position categorizing fuel cell electric vehicles as EZEVs would encourage commercial organizations to invest in all aspects of fuel cell electric engine and vehicle development. On the other hand and not surprisingly, no organization favored regulation of vehicle production quotas.

2. Develop and promulgate fuel composition standards that favor fuel cell electric vehicles.

One motivation for this suggestion is the concern among developers of gasoline fuel cells about the possible effects of residual sulfur in gasoline on fuel cell electric engines. Although the long-term tolerance of fuel processor catalysts to sulfur in gasoline is not known, the possibly serious consequences for PROX and/or stack catalysts argue for the lowest levels of sulfur economically feasible. The prospective high fuel economy of fuel cell electric vehicles will reduce the impact of additional refinery processing and fuel price on vehicle operating cost.

3. Support/foster demonstrations and establish incentives for market introduction.

Because of the anticipated high costs of both, early fuel cell electric vehicles and their supporting infrastructures, provision of incentives to offset as much of this higher cost as possible is considered very important. For example, anticipation of EZEV performance could result in the largest available environmental credits for fuel cell electric vehicles. Beyond excellent environmental performance regarding pollutant emissions, fuel cell engines are expected to be substantially more efficient and thus might be given a “carbon credit” to encourage introduction of an engine option that could be coupled first to natural gas via methanol and, in the longer term, to biofuels (methane, methanol and ethanol from biomass) and to solar, wind and nuclear “non-carbon” energy sources via electricity and hydrogen.